

INVARIANT PROPERTIES OF
A SHEET ASPHALT MIXTURE

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OF A

SHEET ASPHALT MIXTURE

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ABRIDGMENT

Lal, N. B., Goetz, W. H. and Harr, M. E., "Invariant Properties of a Sheet Asphalt Mixture". Presented at the 45th Annual Meeting of the Highway Research Board, Washington, D. C., January 1966. Manuscript copy consists of 13 pages, 3 tables, 11 figures.

Descriptors: sheet asphalt, tension test, shear test, hollow cylinder, compression test, stress-strain-temperature relationships.

The study was undertaken to provide invariant properties of a sheet asphalt mixture. To do this three independent equations were sought which in combination with the two general two-dimensional equations of motion, involving five unknowns, will render the system complete.

The required three equations were determined on the basis of experimental data obtained from two different types of laboratory tests. Uniaxial Tension and Simple Shear tests were chosen for this purpose.

The Uniaxial Tension tests were performed on cylindrical specimens by subjecting them to constant stress at constant temperature and observing the axial and circumferential strains with time. The tests were repeated under different stresses at three temperatures. On the basis of the data obtained from these tests, an equation relating stress (σ_z) to axial strain (ϵ_z) was derived. The equation had the following form:

$$\sigma_z = \left[\frac{T}{c_1} \right]^{-c_2} - \left[\frac{T}{p_1} \right]^{-p_2} \frac{\epsilon_z}{t \frac{\partial \epsilon_z}{\partial t}} ; 40^\circ\text{F} \leq T \leq 100^\circ\text{F}$$

where t stands for time, T for temperature and c_1 , c_2 , p_1 , p_2 are four material constants. A similar expression relating stress (σ_z) to circumferential strain (ϵ_y) was also obtained from the results of these tests.

The Simple Shear tests were performed on thin rectangular specimens by subjecting them to constant shear stress at constant temperature and observing the shear strain with time. The tests were repeated under different stresses at three temperatures. On the basis of these tests, an expression relating shear stress to shear strain was obtained in the same form as given above for Uniaxial Tension tests.

The four material constants as found from the stress-strain expressions derived from the above two types of tests were independent of time and temperature for small values of strain. Since the values of these material constants as determined from the two series of tests were in close agreement, it was indicated that these are also independent of the type of test.

Axial Compression tests were performed on hollow cylindrical specimens to compare the results with those predicted on the basis of the corresponding Uniaxial Tension tests. It was found that for small strains of less than about 0.4 percent, the two tests gave very close results. For large strains, whereas the strain (ordinate)-time (abscissa) plot on log-log scales tended to curve upward at the beginning of failure conditions in Uniaxial Tension tests, the corresponding plots for Axial Compression tests tended to curve downward to lesser slopes, at about the same time.

It was concluded that three independent stress-strain relationships exist as functions of time and temperature. These expressions contain four basic material constants which are independent of time and temperature and type of test.

SYNOPSIS

In this work properties of a sheet asphalt mixture are obtained that are believed to have greater quantitative significance than those usually used to describe bituminous mixtures. The results are based upon Newton's equations of motion under conditions of plane strain. As these equations are two in number but contain five unknowns, laboratory tests were conducted to obtain three additional independent expressions relating the unknowns. Only those parts of the relationships that were found to be reproducible and independent of time, temperature and conditions of test were considered material properties. Four basic material constants were obtained as opposed to the more usual three constants: modulus of elasticity, Poisson's ratio, and coefficient of thermal expansion.

INTRODUCTION

Newton's equations of motion for a two-dimensional system are:

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{yz}}{\partial y} = \gamma + \rho \frac{\partial^2 w}{\partial t^2}; \quad \frac{\partial \tau_{yz}}{\partial z} + \frac{\partial \sigma_y}{\partial y} = \rho \frac{\partial^2 v}{\partial t^2} \quad (1)$$

where σ_z and σ_y are normal stresses and w and v are displacements in the vertical (z) and horizontal (y) directions, respectively; τ_{yz} is the shear stress in the plane under consideration; γ is the unit weight of the mixture, and ρ is its mass unit weight ($\rho = \gamma/g$).

Equations (1) contain five unknowns: σ_z , σ_y , τ_{yz} , w , v . Hence, three more independent expressions relating these are needed to render the system solvable. To achieve this balance, recourse was made to simple laboratory tests conducted under inputs varying with time and temperature wherein pertinent relationships may be obtained from relevant observations.

Any parameters relating the unknowns that are found to be independent of type of test or conditions of loading are material properties of the bituminous mixture studied. Underlying this concept is the requirement that for any material property to have quantitative significance it must, of necessity, reflect the action of the material "in situ". Hence, true properties must remain unchanged (invariant) under transformations from laboratory to field conditions. For properties to be invariant under transformations from a simple laboratory test to very complicated field conditions, they must of necessity also remain constant under different laboratory tests. Using this condition of necessity in combination with Eqns. (1) and conducting different types of simple laboratory tests, with known boundary conditions, those parameters remaining constant were duly noted as material properties.

METHODS OF TESTING

In order to obtain the three equations required for solving the aforementioned two-dimensional deformable system, relevant experimental data had to be obtained from different types of tests. For this purpose Uniaxial Tension and Simple Shear tests were chosen. To verify the material constants as obtained from these tests, an Axial Compression test was utilized. The considerations for the choice of these tests and the experimental techniques employed therein are given below under separate headings for each.

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Uniaxial Tension Tests

To evaluate the material constants expected to be found in the relationships between normal stress and strains along and at right angles to the direction of application of load, a Uniaxial Tension test was performed. This was done because in such a test the shear stresses are zero in these directions and the material may be considered as subject to normal tensile stresses only.

A cylindrical specimen two-inches in diameter and four-inches high was subjected to constant tensile stress at constant temperature and the elongation per inch as well as decrease in radius per inch was noted with time. To reduce the end-effects, the measurements of strain were confined to the middle portion of the specimen. Also, to minimize the errors due to any possible eccentricity during the application of load, the strains were measured at locations 180° apart in the middle portion of the specimen. In this way, by measuring the elongation of the middle one-inch portion and the reduction in diameter at the middle, plots of axial strain versus time and lateral strain versus time, at constant tensile stress, were obtained. By repeating the above procedures for different temperatures, the relationships between normal stress and the axial and lateral strains were obtained as functions of time and temperature.

Figure 1 shows the instrumentation for this test. A simple mechanical device was developed which greatly enhanced the strain measuring technique. This consisted of levers with pointed ends which made contact with the specimen. Deformation of the specimen at the point of contact with the pointed end of the lever was recorded by a dial indicator attached to the lever end away from the specimen. Axial strain in the middle portion of the specimen was determined by the difference in deformations recorded by dial indicators attached to the levers 1 inch apart vertically. The readings of the dial indicators were

estimated up to 0.00005 inch. Change in diameter at mid-height of specimen was recorded by dial indicators with their extensions, machined to fit the curved surface, resting directly on the specimen surface.

Simple Shear Tests

The relationship between shear stress and shear strain was determined from a Simple Shear test wherein the normal stresses may be taken to be zero in the considered planes.

A simple and direct means of determining shear strain as a function of time under constant stress and at constant temperature was achieved by forming a specimen of appropriate thickness, fixing one face and pulling the other parallel face under constant load. A diagrammatic sketch of this test is shown in Figure 2. In deciding upon the thickness of specimens for these Simple Shear tests, the following points were considered:

1. Minimum amount of bending while the specimen is being subjected to simple shearing stress.
2. Non-interference of particles within the specimen.
3. Practicability of fabricating specimens with uniformity or homogeneity of compacted materials.
4. Ability to record the dilation of the specimen while undergoing shearing strain.

After trying several thicknesses with the above points considered, a thickness of 1/4 inch and a specimen size of 4 x 2 inches were chosen.

Axial Compression Tests

A hollow-cylinder compression test was performed in an attempt to verify the material constants as obtained from the Uniaxial Tension and Simple Shear tests. In this test, deformations of the material were observed both in the axial as well as the lateral direction by noting the deformations on the inside

as well as the outside of the hollow cylinder. Again, the tests were performed under constant load and at constant temperature. The instrumentation developed for measuring axial deformations and change in external diameter in the Uniaxial Tension tests was applicable for these tests also. For measuring change in inside diameter, a modification of this lever system using dial indicators was used. This is shown by the diagrammatic sketch of Figure 3.

The hollow cylindrical specimen, having a 2-inch external diameter, 1-inch internal diameter and 4-inch height, was placed on a hollow steel cylinder fitted with two hinged levers. The upper parts of the hinges were machined to correspond to the inside curved surface of the specimen and the lower ends were contacted by extensions of the dial indicators. Changes in the diameter of the hole were recorded with time. Changes in outside diameter were recorded with time by dial indicators resting directly on the surface. Changes in unit thickness of specimen, or lateral strain, were thus calculated from the difference in changes of outside and inside diameters.

SUMMARY OF TEST RESULTS

To obtain the experimental data required for this study, Uniaxial Tension, Simple Shear and Axial Compression tests were performed. In this order, the results of these tests are summarized here. Complete test results for Uniaxial Tension and Simple Shear tests are tabulated, but only the data for tests at 77°F are presented in plot form, including those for the axial compression tests.

The test results for the Uniaxial Tension tests are given in Tables 1 and 2 for axial and circumferential strain, respectively. As can be seen from Figure 4, the axial strain of specimens under constant stress and constant temperature, when plotted as ordinate against time on log-log scales gave a straight line relation-

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ship in the pre-failure region. As failure started to take place with the appearance of minute cracks in the middle portion of specimen, the straight line on the log-log plot tended to curve upward. It was found convenient to characterize the straight line portion of the plot by its slope and axial strain at one minute (it being a log scale). Within the range of temperatures and stress-levels tested, the following points of interest were observed from the Uniaxial Tension test results:

At constant temperature, the axial strain at one minute did not vary proportionally with applied stress. The deviation from proportionality increased with increasing temperature as well as with increasing applied stress. The slopes of the straight-line portions of the log-log plots varied with the applied stress and temperature. The slopes became steeper with increase in applied stress at constant temperature. For an incremental change in stress, the corresponding change in slope was greater at higher temperatures.

The circumferential strain when plotted as ordinate against time on log-log scales also gave a straight-line relationship. See Figure 5. The same trends as observed for axial strains were observed for circumferential strains.

A study of Poisson's ratio for the material as determined from the Uniaxial Tension test data showed it to be a function of applied stress, time and temperature. Whereas at 40°F its value was found to be almost independent of applied stress, as would be the case for an elastic material, at higher temperatures it decreased with increasing applied stress.

Results for the Simple Shear tests are given in Table 3. As can be seen from Figure 6, the shearing strain in the specimen under constant shear stress and constant temperature, when plotted as ordinate against time on log-log scales, gave a straight-line relationship in the pre-failure region. The shearing strain-

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time relationships showed the same trends with regard to temperature and applied stress as were observed in the axial strain-time relationships as determined by the Uniaxial Tension tests. This was an indication of the fact that the same basic material properties were being reflected in these two types of tests.

For the Axial Compression tests, the log-log plots of axial strain vs. time (Figure 7) were found not to be continuous straight lines for the entire range. The plots were straight lines up to a certain percentage of deformation after which they curved downward to lesser slopes. As shown in Figure 8, a similar result was found for circumferential strains recorded in the axial compression tests. The initial straight-line portions of the Axial Compression test plots showed the same trends with regard to applied stress and temperature as were observed in the axial strain-time plots from the Uniaxial Tension tests. It was also observed from the Axial Compression test results that strains up to about 0.4 percent can be quite satisfactorily predicted from the Uniaxial Tension tests.

DERIVATION OF STRESS-STRAIN EXPRESSIONS

The derivations of stress-strain expressions from Uniaxial Tension and Simple Shear test results are based on the following observations:

- 1) The strain-time plots in the pre-failure regions on log-log scales were straight lines.
- 2) The slopes of these straight lines varied with the applied stress and temperature.

Derivation of the relationship between normal stress σ_z and axial strain ϵ_z as a function of time and temperature is as follows. Axial strain-time plots on log-log scales being straight lines in pre-failure regions can be represented as:

$\log \epsilon_z = \log k_1 + k_2 \log t$ where t stands for time, k_2 is the slope of the straight line and k_1 is the axial strain at unit time. Differentiating with respect to t , we get

$$\frac{1}{\epsilon_z} \frac{\partial \epsilon_z}{\partial t} = \frac{k_2}{t} \quad (1)$$

The slopes k_2 of these straight lines varied linearly with stress in the test range as shown in Figure 9 and hence yields the relation

$$\sigma_z = \frac{I(T)}{S(T)} - \frac{1}{S(T)} - \frac{1}{k_2} \quad (2)$$

where $I(T)$ and $S(T)$ are the intercepts on $1/k_2$ axis and slopes of the straight lines respectively as a function of temperature T .

Figure 10 shows on log-log scales a straight line relationship between temperature T and the ratio $\frac{I(T)}{S(T)}$ i.e., $\frac{I(T)}{S(T)} = \left[\frac{T}{c_1} \right]^{-c_2}$ where c_1 and c_2 are constants. Similarly, the log-log plot of Figure 11 shows $\frac{1}{S(T)} = \left[\frac{T}{p_1} \right]^{-p_2}$ where p_1 and p_2 are constants.

Substituting these values of $\frac{I(T)}{S(T)}$ and $\frac{1}{S(T)}$ and also the value of k_2 from (1) in equation (2), we get:

$$\sigma_z = \left[\frac{T}{c_1} \right]^{-c_2} - \left[\frac{T}{p_1} \right]^{-p_2} \frac{\epsilon_z}{t \frac{\partial \epsilon_z}{\partial t}}$$

where c_1, c_2, p_1, p_2 are material constants independent of time and temperature.

the \mathcal{H}^1 -norm. The \mathcal{H}^1 -norm is defined by $\|u\|_{\mathcal{H}^1} = \left(\int_{\mathbb{R}^d} |\nabla u|^2 dx \right)^{1/2}$. The \mathcal{H}^1 -norm is a norm on the space of functions u with $\nabla u \in L^2(\mathbb{R}^d)$. The \mathcal{H}^1 -norm is a norm on the space of functions u with $\nabla u \in L^2(\mathbb{R}^d)$.

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DISCUSSION OF STRESS-STRAIN EXPRESSIONS

From Uniaxial Tension test results, the expression relating the normal tensile stress (σ_z) to axial strain (ϵ_z) was found to be:

$$\sigma_z = \left[\frac{T}{c_1} \right]^{-c_2} - \left[\frac{T}{p_1} \right]^{-p_2} t \frac{\epsilon_z}{\frac{\partial \epsilon_z}{\partial t}}$$

where t stands for time, T for temperature and c_1 , c_2 , p_1 , p_2 are material constants. An expression of the same form relating σ_z to circumferential strain (ϵ_y) was found as:

$$\sigma_z = \left[\frac{T}{c_1'} \right]^{-c_2'} - \left[\frac{T}{p_1'} \right]^{-p_2'} t \frac{\epsilon_y}{\frac{\partial \epsilon_y}{\partial t}}$$

Assuming the material to be isotropic and homogeneous, the following equations can be written:

$$\sigma_y = \left[\frac{T}{c_1} \right]^{-c_2} - \left[\frac{T}{p_1} \right]^{-p_2} t \frac{\epsilon_y}{\frac{\partial \epsilon_y}{\partial t}} = \left[\frac{T}{c_1'} \right]^{-c_2'} - \left[\frac{T}{p_1'} \right]^{-p_2'} t \frac{\epsilon_z}{\frac{\partial \epsilon_z}{\partial t}}$$

From the Simple Shear test results, the expression relating the shear stress (τ_{yz}) to shear strain (γ_{yz}), was found to be of similar algebraic form; namely,

$$\tau_{yz} = \left[\frac{T}{c_1''} \right]^{-c_2''} - \left[\frac{T}{p_1''} \right]^{-p_2''} t \frac{\gamma_{yz}}{\frac{\partial \gamma_{yz}}{\partial t}}$$

where c_1'' , c_2'' , p_1'' and p_2'' are material constants. The values of the four material constants as determined from Uniaxial Tension test results are:

$$\begin{array}{ll} c_1 = 130 & c_2 = 5.15 \\ p_1 = 98 & p_2 = 6.00 \end{array}$$

The corresponding material constants as determined from the Simple Shear test results are:

$$\begin{array}{ll} c_1'' = 150 & c_2'' = 4.40 \\ p_1'' = 108 & p_2'' = 5.15 \end{array}$$

A comparison of these material constants as obtained from the two types of tests show that they are quite close, considering the experimental limitations involved in the study. The stress-strain expressions from these two types of tests show that there are at least four material constants independent of time and temperature. These expressions when used to predict strains in an Axial Compression test gave reasonably good results for small strains up to 0.4% only, as observed in the previous section. For strains greater than 0.4% it appears that a different deformation mechanism is operating in compression as compared to tension tests. However, it must be recognized that pure compression was probably not achieved in the test performed and that the measurements made were less than ideal.

It may be pointed out here that these expressions can be usefully employed in devising a laboratory test for bituminous mixtures which would evaluate the constants for the material. Such a test would be quantitative and not just qualitative like the triaxial test used for testing bituminous mixtures.

The existence of at least four material constants, independent of time and temperature, as obtained from two different types of tests in this study, gives promise of more meaningful quantitative evaluation in the mixtures. The precise purpose of this study, as stated in the outline of the investigation was to determine more meaningful properties for a sheet-asphalt mixture than those customarily used. This has been achieved with the three stress-strain expressions

1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 2679, 26

obtained from relevant experimental data, which, with the two equations of motion in two dimensions, give a set of five equations and five unknowns as follows:

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{yz}}{\partial y} = z + m \frac{\partial^2 w}{\partial t^2} \dots \dots \dots (a)$$

$$\frac{\partial \tau_{yz}}{\partial z} + \frac{\partial \sigma_y}{\partial y} = m \frac{\partial^2 v}{\partial t^2} \dots \dots \dots (b)$$

$$\begin{aligned} \sigma_z &= \left[\frac{T}{c_1} \right]^{-c_2} - \left[\frac{T}{p_1} \right]^{-p_2} \frac{\partial w / \partial z}{t \frac{\partial^2 w}{\partial t \partial z}} \\ &= \left[\frac{T}{c_1} \right]^{-c_2'} - \left[\frac{T}{p_1} \right]^{-p_2'} \frac{\partial v / \partial y}{t \frac{\partial^2 v}{\partial t \partial y}} \dots \dots \dots (c) \end{aligned}$$

$$\begin{aligned} \sigma_y &= \left[\frac{T}{c_1} \right]^{-c_2} - \left[\frac{T}{p_1} \right]^{-p_2} \frac{\partial v / \partial y}{t \frac{\partial^2 v}{\partial t \partial y}} \\ &= \left[\frac{T}{c_1} \right]^{-c_2'} - \left[\frac{T}{p_1} \right]^{-p_2'} \frac{\partial w / \partial z}{t \frac{\partial^2 w}{\partial z \partial t}} \dots \dots \dots (d) \end{aligned}$$

$$\tau_{yz} = \left[\frac{T}{c_1} \right]^{-c_2''} - \left[\frac{T}{p_1} \right]^{-p_2''} \frac{\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}}{t \left[\frac{\partial^2 w}{\partial t \partial y} + \frac{\partial^2 v}{\partial t \partial z} \right]} \dots \dots \dots (e)$$

It must be recognized, however, that the three stress-strain expressions obtained from experimental data are valid only for the range of temperatures and stress-levels for which the material was tested in this study.

The first part of the report is a general introduction to the subject of the study. It is followed by a description of the methods used in the investigation. The results of the study are then presented in a series of tables and figures. The final part of the report is a discussion of the results and a conclusion.

The second part of the report is a detailed description of the methods used in the investigation. This includes a description of the experimental apparatus, the procedures used for data collection, and the methods used for data analysis.

The third part of the report is a presentation of the results of the study. This is done in a series of tables and figures. The tables show the raw data, and the figures show the data in a more graphical form.

The fourth part of the report is a discussion of the results and a conclusion. This part discusses the implications of the results and compares them with previous studies. It also provides a conclusion to the study.

The fifth part of the report is a list of references. This list includes all the sources used in the study, including books, articles, and other documents.

The sixth part of the report is an appendix. This appendix contains additional information that is not included in the main body of the report, such as raw data, additional figures, and other supporting material.

The seventh part of the report is a list of figures. This list includes all the figures used in the study, including tables, graphs, and other visual aids.

The eighth part of the report is a list of tables. This list includes all the tables used in the study, including data tables, summary tables, and other tables.

The ninth part of the report is a list of figures. This list includes all the figures used in the study, including tables, graphs, and other visual aids.

CONCLUSIONS

The following conclusions have been drawn from the experimental data obtained for the sheet-asphalt mixture, within the range of temperatures and stress-levels for which it was tested in this investigation:

1. Three independent stress-strain relationships exist as functions of time and temperature which together with the two-dimensional equations of motion, give a system of five equations containing five unknowns.

2. For the sheet asphalt mixture tested, there exist at least four basic material constants independent of time and temperature as opposed to the usual modulus of elasticity and Poisson's ratio constants assumed in elastic theory. These four basic material constants exist in the tensile stress-axial strain expression derived from Uniaxial Tension test results and also in the shear stress-shear strain expression derived from Simple Shear test results. From the fact that the magnitude of the material constants as determined from two different types of tests, performed for a number of different conditions of time and temperature, were quite close to each other, it may be concluded that these material constants are independent of the type of test. As the results from Axial Compression tests corresponded reasonably well with those predicted from Uniaxial Tension test results for strains less than about 0.4 percent, it may be concluded that the derived expressions hold for both tension and compression of the material for very small strains.

on the basis of the information available to the Committee at the time of its report. The Committee has not been able to determine whether the information was obtained from a source who is reliable or not.

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1. The first part of the report deals with the general situation of the country and the position of the various groups of the population.

2. The second part of the report deals with the economic situation of the country and the position of the various groups of the population.

3. The third part of the report deals with the social situation of the country and the position of the various groups of the population.

4. The fourth part of the report deals with the cultural situation of the country and the position of the various groups of the population.

5. The fifth part of the report deals with the political situation of the country and the position of the various groups of the population.

6. The sixth part of the report deals with the international situation of the country and the position of the various groups of the population.

7. The seventh part of the report deals with the future of the country and the position of the various groups of the population.

TABLE 1

Axial Strain - Time Relationships

For

Uniaxial Tension Tests

40° F				77° F				100° F			
Applied Tensile Stress	Axial Strain at One-Minute	Slope of Axial Strain vs. Time Plot (log-log)	Applied Tensile Stress	Axial Strain at One-Minute	Slope of Axial Strain vs. Time Plot (log-log)	Applied Tensile Stress	Axial Strain at One-Minute	Applied Tensile Stress	Axial Strain at One-Minute	Slope of Axial Strain vs. Time Plot (log-log)	
Psi	0.0001 in./in.		Psi	0.0001 in./in.		Psi	0.0001 in./in.	Psi	0.0001 in./in.		
18.43	2.55	1:1.95	1.70	11.5	1:2.80	0.75	7.2	1:4.40			
30.43	4.40	1:1.90	2.43	15.0	1:2.50	1.07	18.5	1:3.70			
40.43	6.60	1:1.85	4.43	28.5	1:2.00	1.43	26.0	1:3.20			
52.43	9.60	1:1.80	5.43	39.0	1:1.80	2.43	60.0	1:2.40			

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	12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TABLE 2

Circumferential Strain - Time Relationships

For

Uniaxial Tension Tests

40° F				77° F				100° F			
Applied Tensile Stress	Circum- ferential Strain	Slope of Circum- ferential Strain vs. Time Plot (log-log)	Applied Tensile Stress	Circum- ferential Strain	Slope of Circum- ferential Strain vs. Time Plot (log-log)	Applied Tensile Stress	Circum- ferential Strain	Applied Tensile Stress	Circum- ferential Strain	Slope of Circum- ferential Strain vs. Time Plot (log-log)	
Psi	One-Minute 0.0001 in./in.		Psi	One-Minute 0.0001 in./in.		Psi	One-Minute 0.0001 in./in.	Psi	One-Minute 0.0001 in./in.		
18.43	1.18	1:2.00	1.70	4.25	1:2.40	0.75	3.25	1:3.00			
30.43	1.75	1:1.95	2.43	5.50	1:2.30	1.07	6.5	1:2.85			
40.43	2.75	1:1.90	4.43	8.50	1:2.20	1.43	10.0	1:2.75			
52.43	3.75	1:1.85	5.43	11.0	1:2.12	2.43	20.0	1:2.50			

TABLE 3

Shear Strain - Time RelationshipsForSimple Shear Tests

40° F				77° F				100° F			
Applied Shear Stress Psi	Shear Strain at One-Minute 0.0001 in./in.	Slope of Shear Strain vs. Time Plot (log-log)	Applied Shear Stress Psi	Shear Strain at One-Minute 0.0001 in./in.	Slope of Shear Strain vs. Time Plot (log-log)	Applied Shear Stress Psi	Shear Strain at One-Minute 0.0001 in./in.	Applied Shear Stress Psi	Shear Strain at One-Minute 0.0001 in./in.	Slope of Shear Strain vs. Time Plot (log-log)	Slope of Shear Strain vs. Time Plot (log-log)
5.64	8.0	1:2.55	1.73	30	1:3.00	0.563	34.0			1:4.50	
10.05	13.6	1:2.50	3.32	56.0	1:2.80	0.950	56.0			1:4.00	
18.3	24.4	1:2.45	4.83	80.0	1:2.60	1.35	88.0			1:3.50	
23.82	32.0	1:2.40	6.45	114.0	1:2.50	1.732	110.0			1:3.38	
			8.02	146.0	1:2.30						

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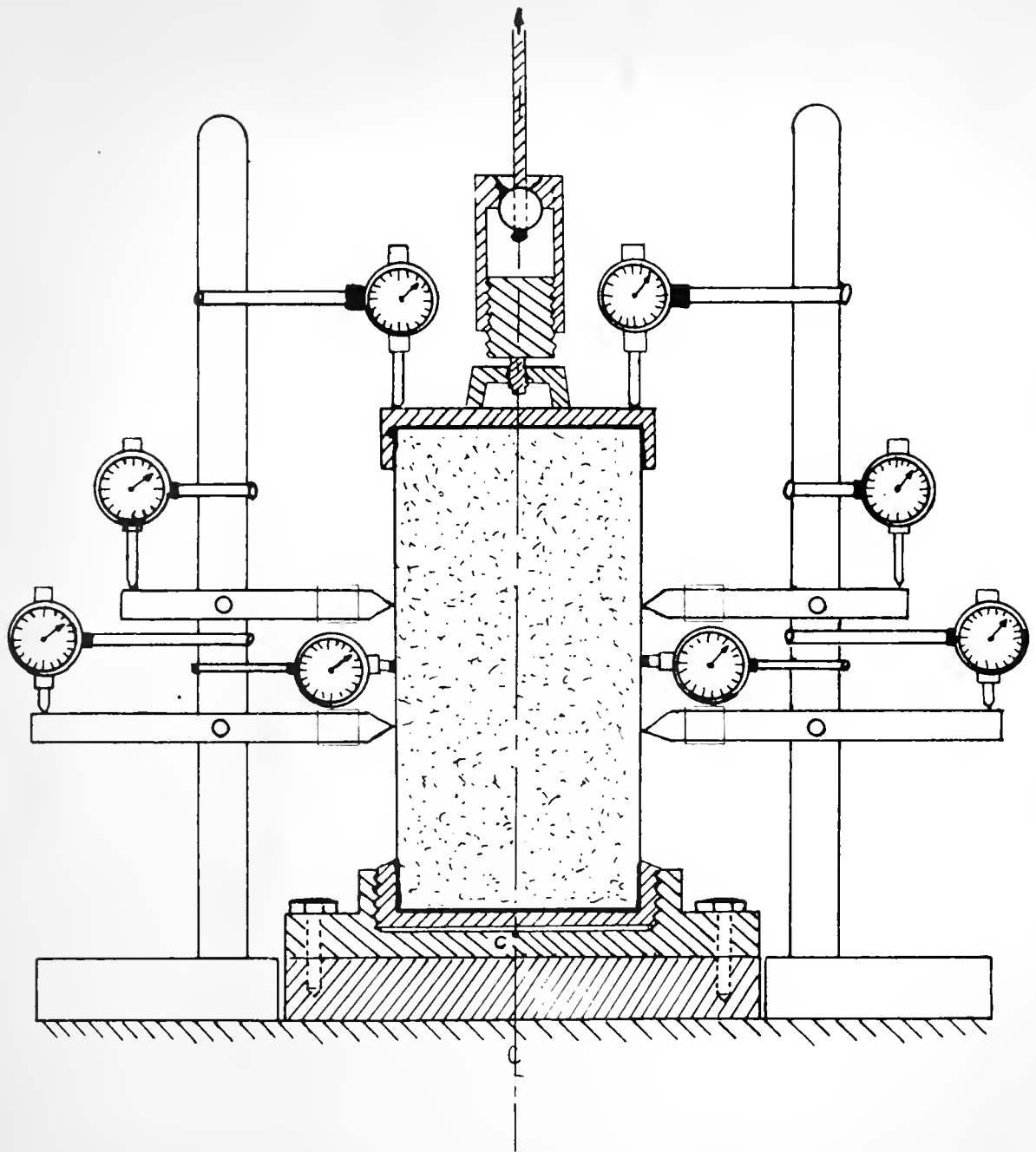


Figure 1 Diagrammatic Sketch Showing Instrumentation of a Uniaxial Tension Test.

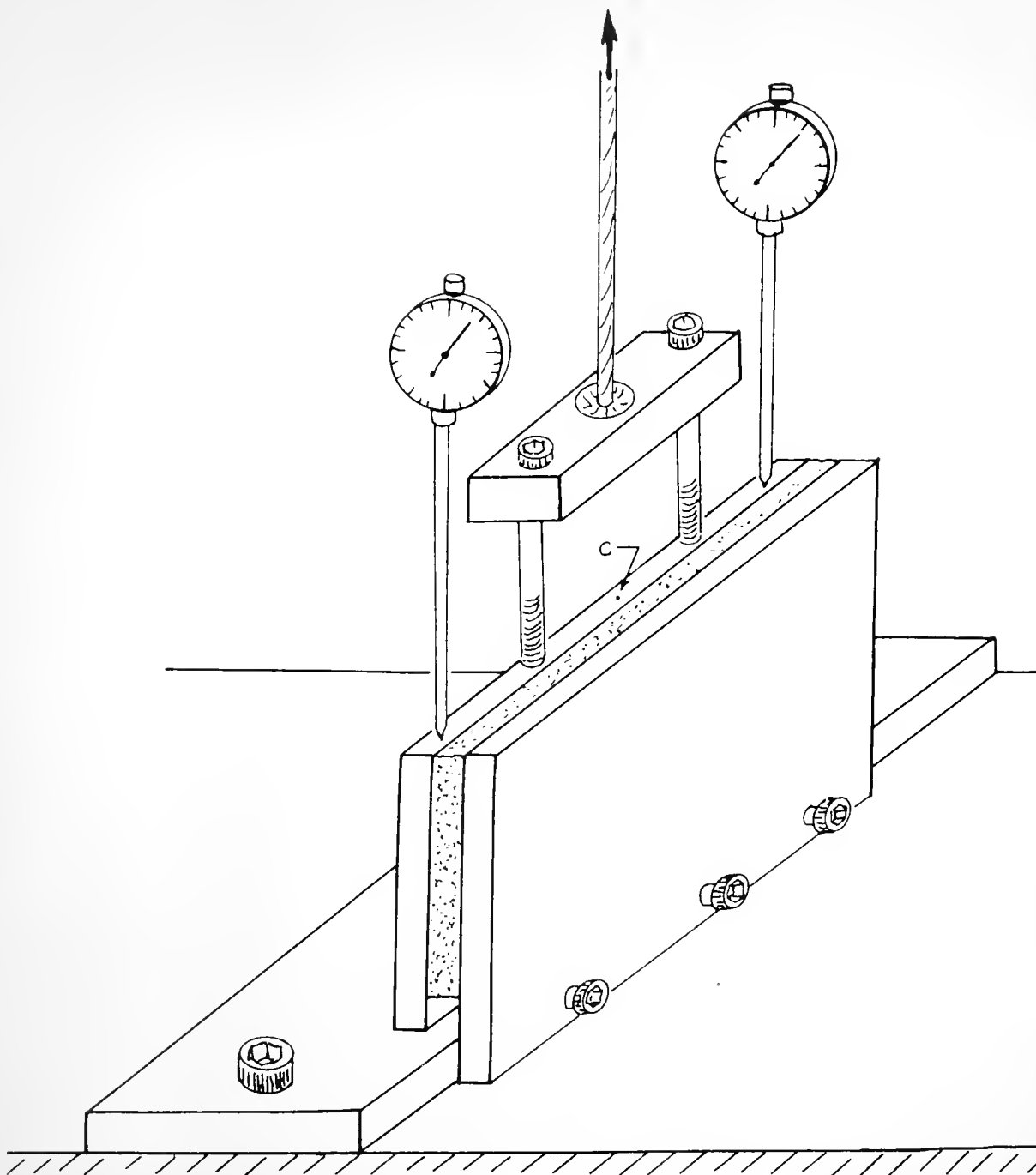


Figure 2 Diagrammatic Sketch Showing Instrumentation of a Simple Shear Test.

UNIAXIAL TENSION TEST RESULTS

AXIAL STRAIN vs. TIME CURVES

TEMPERATURE = 77°F

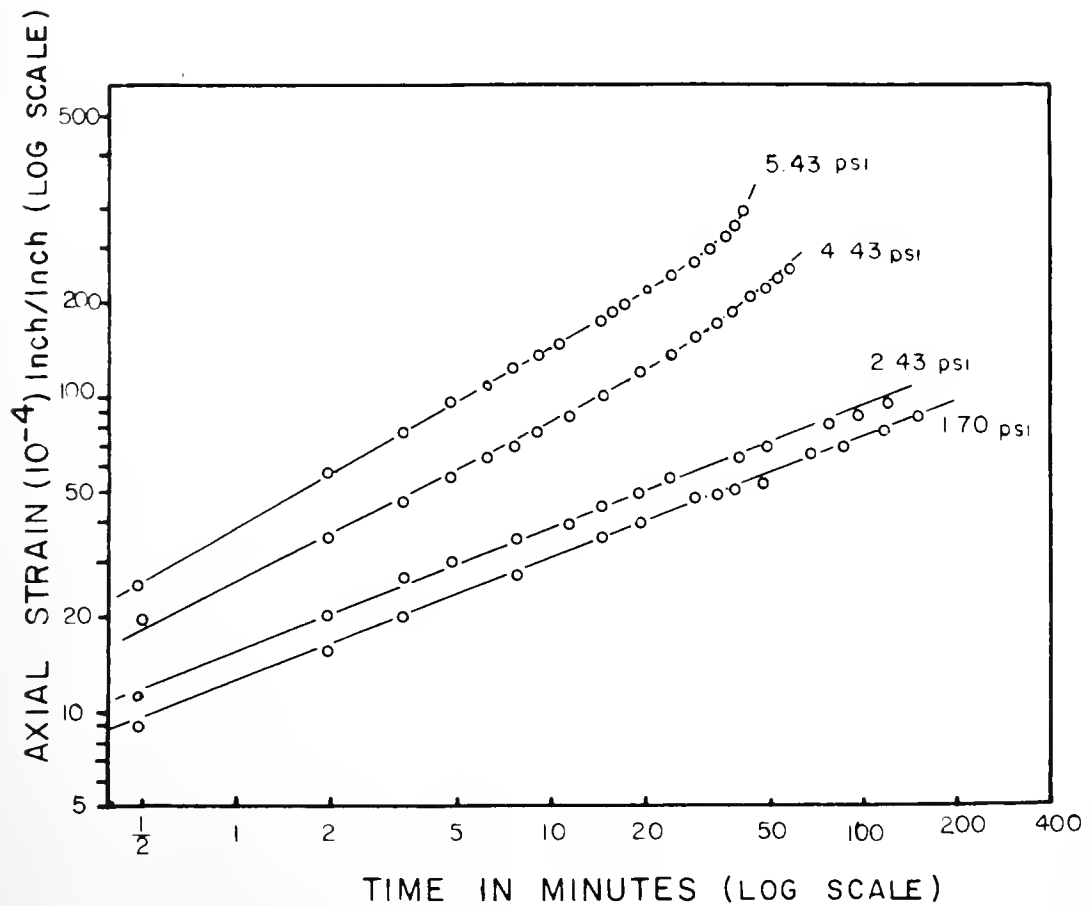


FIG. 4

UNIAXIAL TENSION TEST RESULTS

CIRCUMFERENTIAL STRAIN vs.
TIME CURVES

TEMPERATURE = 77°F

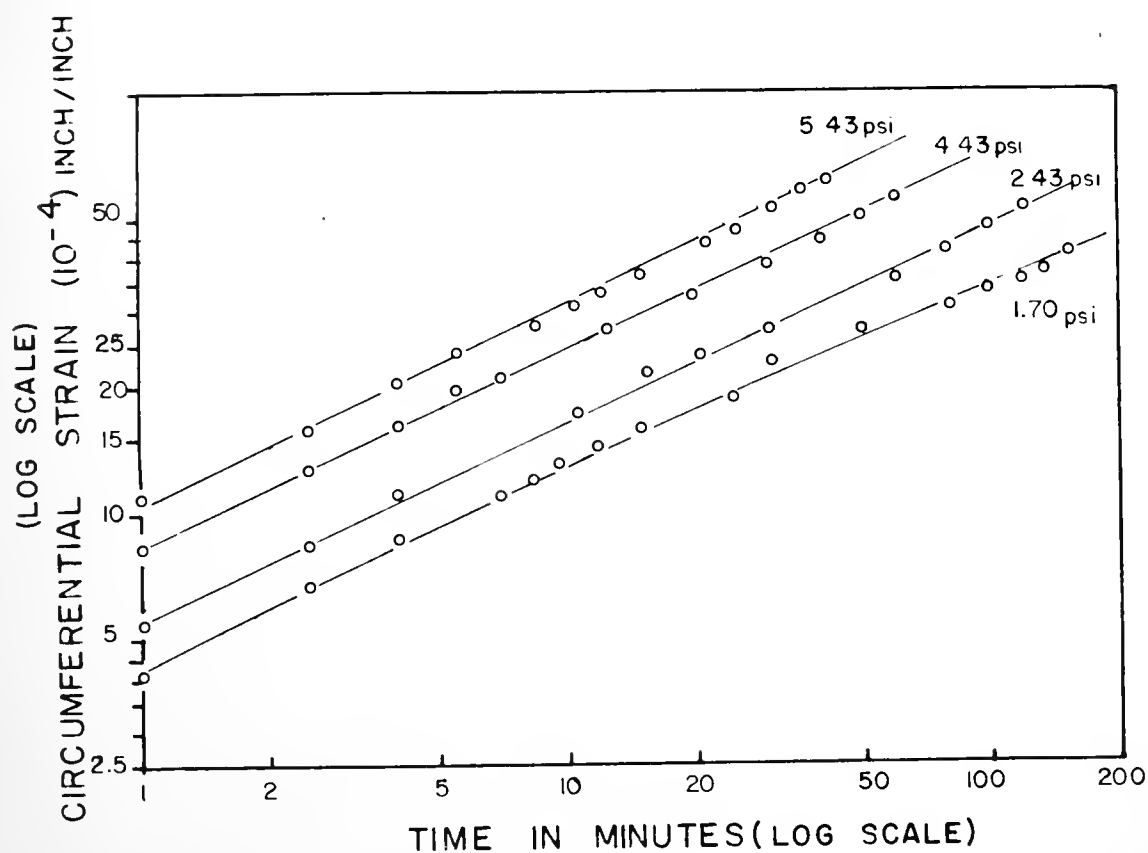


FIG. 5

SIMPLE SHEAR TEST RESULTS

SHEAR STRAIN vs. TIME CURVES

TEMPERATURE = 77°F

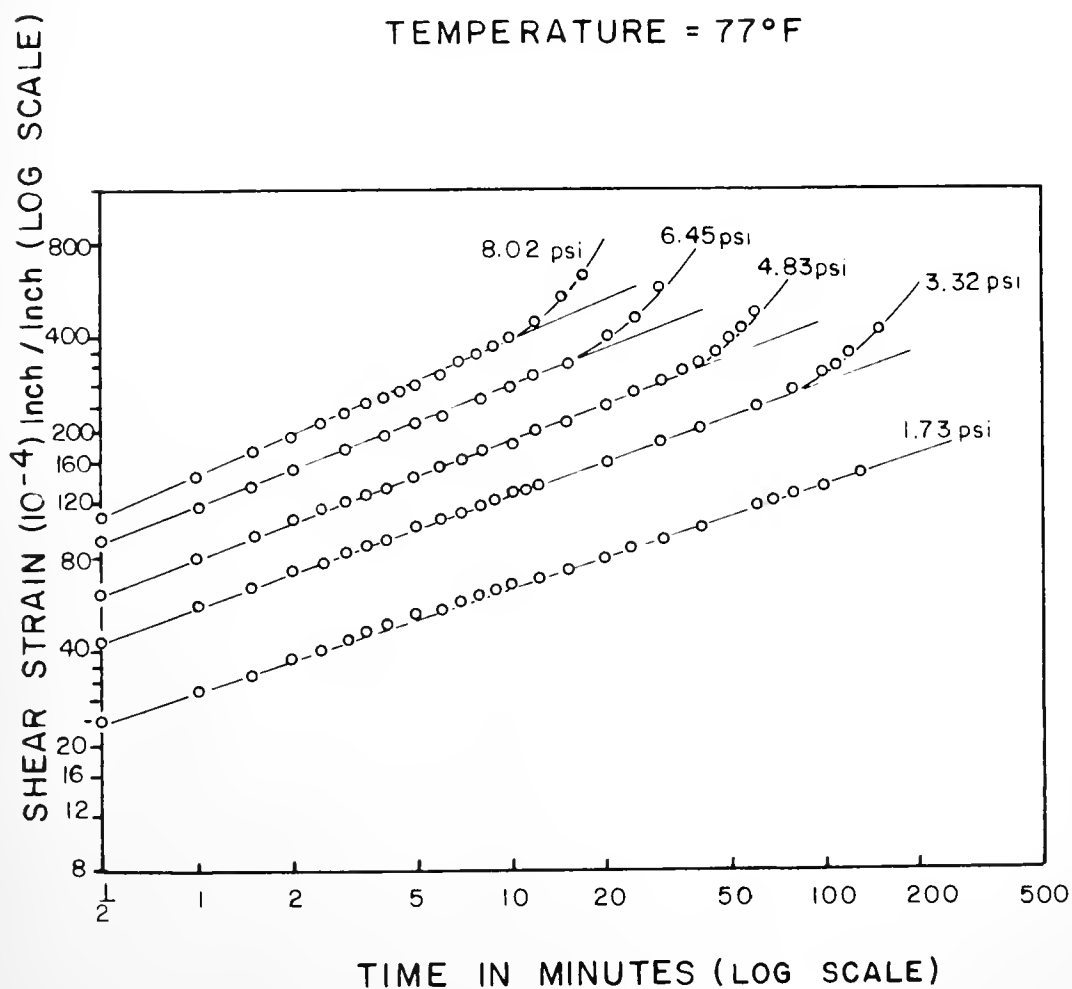


FIG. 6

AXIAL COMPRESSION TEST RESULTS

AXIAL STRAIN vs. TIME
CURVES

TEMPERATURE = 77°F

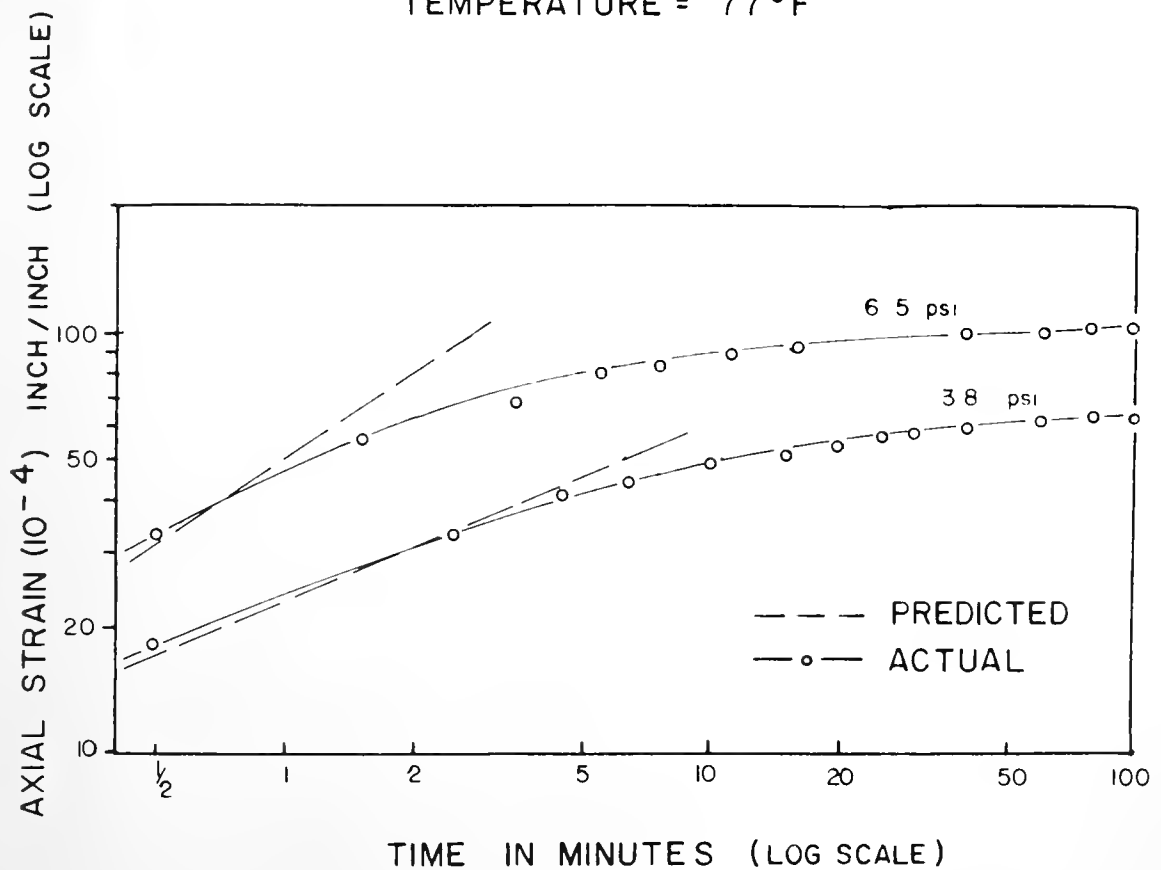


FIG. 7

AXIAL COMPRESSION TEST RESULTS

CIRCUMFERENTIAL STRAIN vs. TIME
CURVES

TEMPERATURE = 77°F.

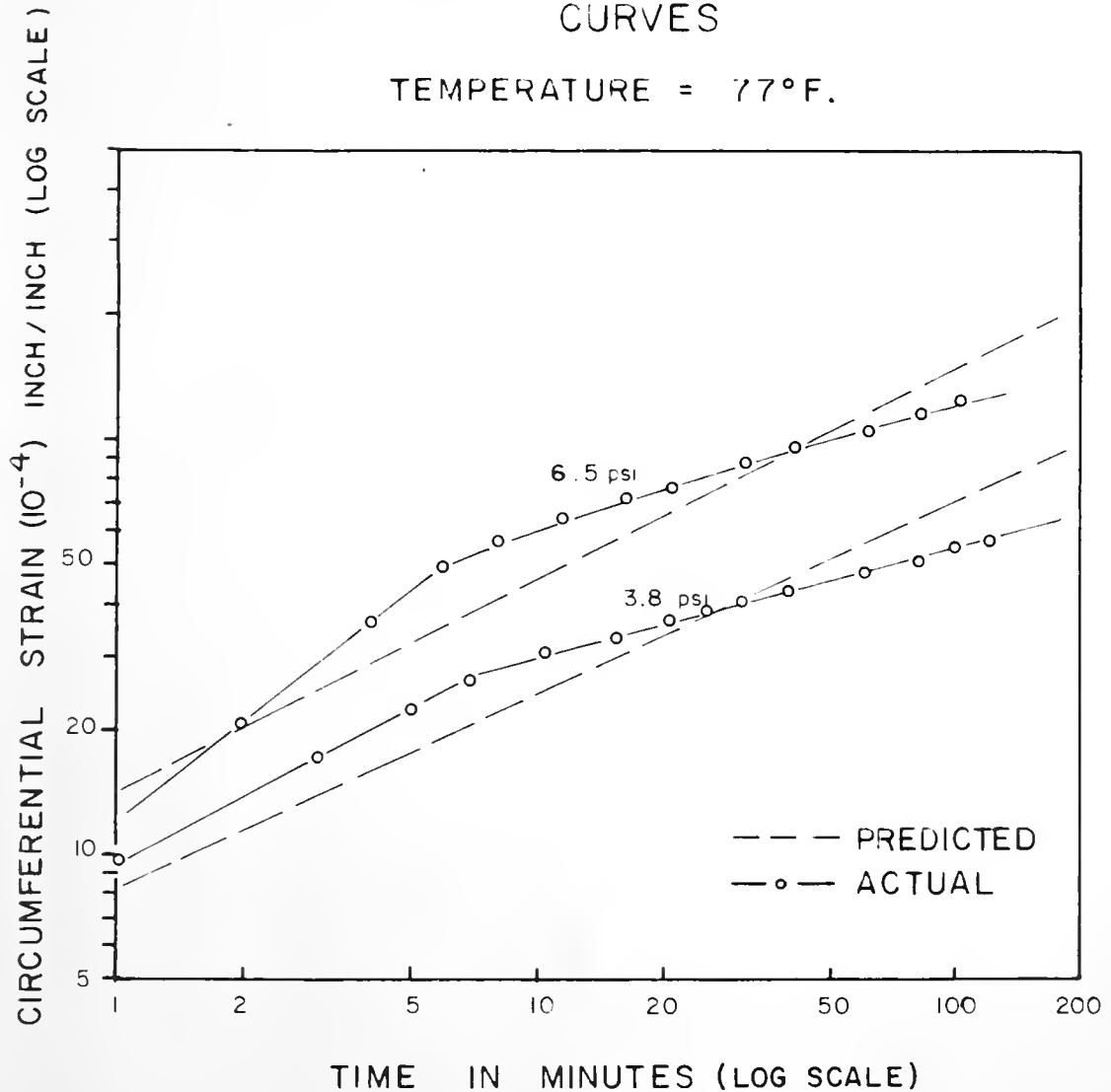


FIG. 8

UNIAXIAL TENSION TEST RESULTS

$1/K_2$ vs. σ_z

$1/K_2$ = RECIPROCAL OF SLOPE OF AXIAL STRAIN vs. TIME
LOG-LOG PLOT

σ_z = TENSILE STRESS IN PSI

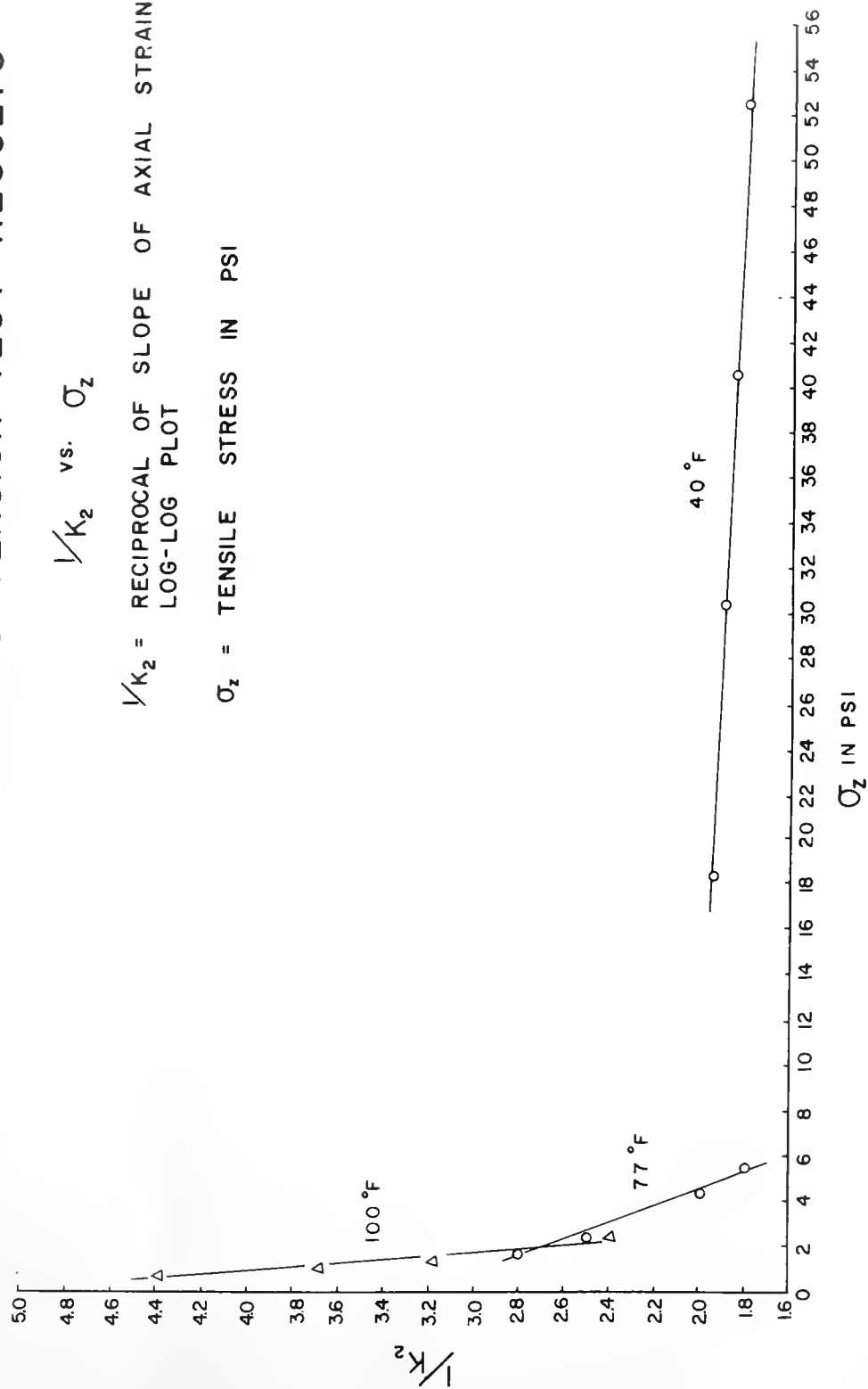


FIG. 9

UNIAXIAL TENSION TEST RESULTS

$\text{LOG} [I(T)/S(T)] \text{ vs. } \text{LOG}(T)$

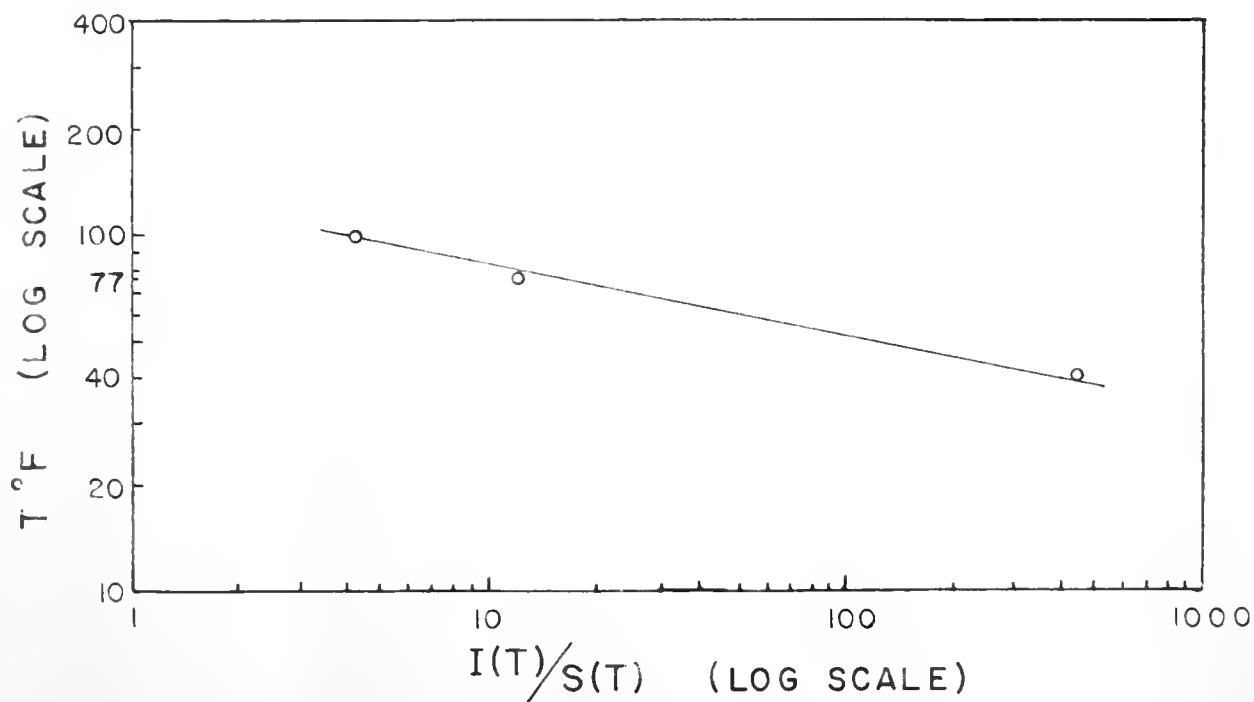


FIG. 10

UNIAXIAL TENSION TEST RESULTS

$$\text{LOG} \left[\frac{l}{S(T)} \right] \text{ vs. } \text{LOG}(T)$$

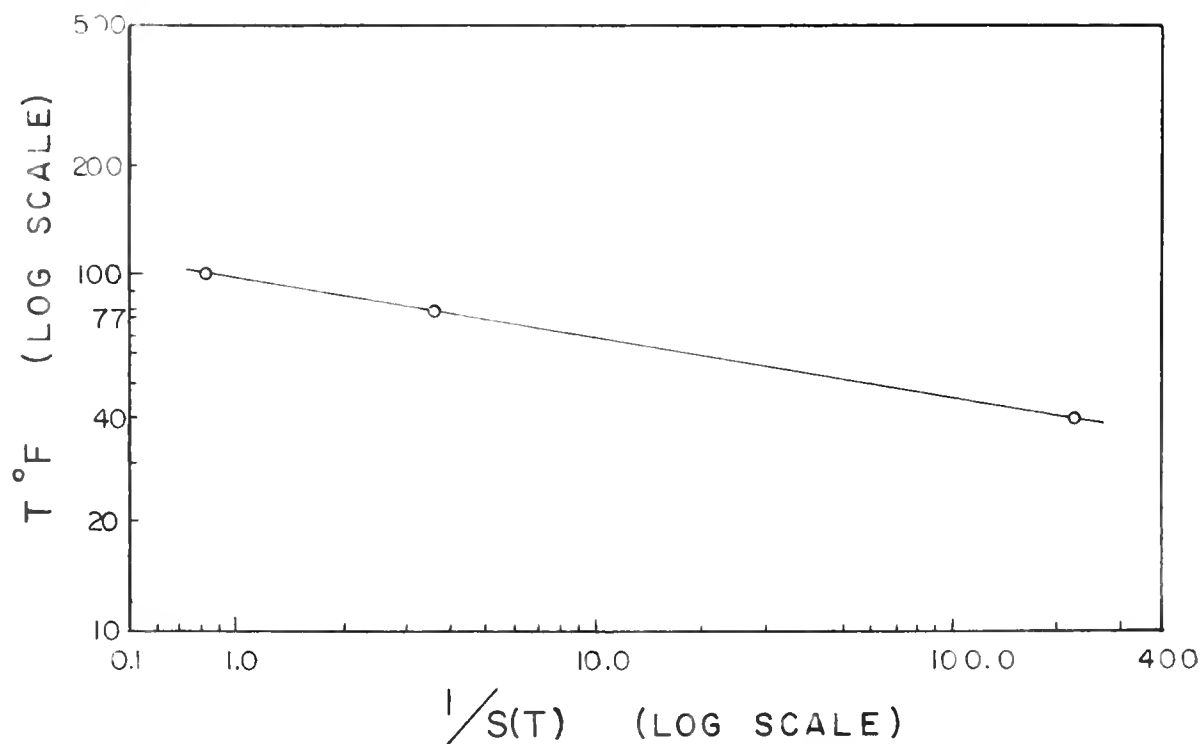


FIG. II

